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Description

SYSTEM AND METHOD FOR MONITORING TORQUE IN AN ELECTRIC MOTOR

BACKGROUND OF INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates to a system and method for monitoring torque in an electric motor.

[0003] 2. Background Art

[0004] With the increasing use of electric motors to drive mechanical systems--e.g., as an alternative to an internal combustion engine to power a vehicle--the need for effective motor control systems is increasingly important. A motor control system may monitor various system components, such as the electric motor itself, sensors used to monitor and provide information about the operation of the electric motor, or both. One such controller arrangement is described in U.S. Patent No. 5,670,856 issued to

Le et al. on September 23, 1997. Le et al. describes a motor controller arrangement for an apparatus that is driven by a number of redundant electric motors. Various motor parameters such as position, speed, and current, are monitored by a plurality of controllers which exchange data over a data bus. The redundant arrangement is configured such that each control channel carries a portion of the overall system load. If one of the channels fails, the remaining channels increase their operational capacity to allow full operation of the driven apparatus.

[0005] In order for a motor control system to be effective, the associated monitoring systems must be equally effective. When an electric motor is used to drive a vehicle, monitoring a number of motor parameters is important. For example, knowing the motor speed may be important for accurately determining the speed of the vehicle. The motor speed may also be used to determine the overall power output by the motor. Another important motor parameter is the motor torque. A vehicle operator commands the vehicle to provide a certain acceleration; this acceleration is processed into a motor torque command. The torque output of the motor should closely match the torque command; otherwise, the vehicle operator may re-

ceive unexpected results. Therefore, there exists a need for monitoring torque in an electric motor, thereby helping to ensure the accuracy of motor torque determinations, so that motor driven systems can be effectively operated.

SUMMARY OF INVENTION

[0006] Accordingly, the invention provides a method for monitoring torque in an electric motor having a power source connected thereto is provided. The method includes measuring current of the motor, determining speed of the motor, and determining a first torque. The first torque is a function of at least the measured current. Power output from the power source is determined, a power loss for the motor is determined, and a second torque is determined. The second torque is a function of at least the power output from the power source, the determined power loss, and the motor speed. The first torque is compared to the second torque when the motor speed is above a predetermined speed.

[0007] The invention also provides a method for monitoring torque in an electric motor disposed in a vehicle having an engine and a power source. The power source is connected to the motor and at least one other vehicle electri-

cal load. The method includes measuring current of the motor, determining a first torque based on the measured current, and determining speed of the motor. A first motor power is also determined. The first motor power is a function of power output from the power source and a power loss for the motor. The power loss includes at least one of an electrical power loss of the motor, a mechanical power loss of the motor, and a power consumed by the at least one other vehicle electrical load. A second torque is determined. The second torque is a function of at least the first motor power and the motor speed. The first torque is compared to the second torque when the motor speed is above a predetermined speed.

[0008] The invention further provides a system for monitoring torque in an electric motor having a power source connected thereto. The motor is in communication with a motor controller, a first sensor configured to facilitate determination of motor speed, and at least one current sensor for measuring motor current. The system includes a first controller in communication with the motor controller and the sensors. The first controller is configured to receive an input related to the motor speed from the first sensor. It is also configured to receive an input related to

the motor current from the at least one current sensor. The controller is further configured to determine a first motor power, first and second torques, and to compare the first torque to the second torque when the motor speed is above a predetermined speed. The first motor power is a function of power output from the power source and a power loss for the motor. The first torque is a function of at least the motor current, and the second torque is a function of at least the first motor power and the motor speed.

BRIEF DESCRIPTION OF DRAWINGS

[0009] Figure 1 is a schematic representation of a portion of a vehicle including a system in accordance with the present invention;

[0010] Figure 2 is a detailed schematic representation of the system shown in Figure 1;

[0011] Figure 3 is a flow chart illustrating a method in accordance with the present invention;

[0012] Figures 4A and 4B show simulation results of a one phase voltage fault in an electric motor;

[0013] Figure 5 shows simulation results for a polarity fault in an electric motor; and

[0014] Figures 6A, 6B and 6C show simulation results for a posi-

tion sensor fault, wherein the position sensor is configured to monitor the position of an electric motor.

DETAILED DESCRIPTION

[0015] Figure 1 is a schematic representation of a system 10 in accordance with the present invention. A vehicle, not shown in its entirety, includes an engine 12 and a motor, or integrated starter generator (ISG) 14. Connected to the ISG 14 is a power transfer unit (PTU) 16, which may be a conventional transmission, a continuous variable transmission (CVT), or other apparatus for transferring power from the engine 12 and the ISG 14 to vehicle wheels 18. A disconnect clutch 20 is disposed between the engine 12 and the ISG 14, and can be used to selectively disconnect the engine 12 from the ISG 14. This allows torque to be provided to the vehicle wheels 18 from both the engine 12 and the ISG 14, or alternatively, from the ISG 14 alone.

[0016] A power source, or battery 22, is connected to the ISG 14, which may receive electric power from the battery 22, or charge the battery 22 when the ISG 14 is being run in a regenerative mode. Of course, other power sources may be used in place of a battery--e.g., a fuel cell or an ultra-capacitor, just to name two. The battery 22 also provides power to other vehicle devices, such as an air conditioning

system, power steering pump, etc. A DC/DC converter (not shown) may also be used to reduce the voltage from the battery 22 to supply low voltage loads. Such low voltage loads may include a stereo system, mirror lights, etc. All of these electrical loads are represented by block 24 in Figure 1.

[0017] The system 10 includes a first controller, or motor control unit (MCU) 26, which controls operation of the ISG 14. As explained more fully below, the MCU 26 also provides torque monitoring for the ISG 14. A second controller 28 is provided for verifying the torque monitoring of the MCU 26, and is therefore shown as a separate hardware device. Alternatively, the controller 28 could be integrated into an existing controller separate from the MCU 26. For example, the controller 28 could be a software controller integrated into an existing powertrain control module (PCM) or a transaxle control module (TCM) in communication with the MCU 26.

[0018] The system 10, including the MCU 26 and the controller 28, is shown in greater detail in Figure 2. The first elements of the MCU 26 include standard motor control elements, well known to those in the art, and are therefore described here with limited detail. For example, a field

oriented torque controller 30 receives a variety of inputs, and then outputs voltages to a transformation function 32. The inputs received by the torque controller 30 include a reference torque (T_{ref}) which is a torque command based on an acceleration request from a vehicle operator. The torque controller 30 may also receive a shutdown command for the ISG 14, depending on vehicle requirements and the outcome of the torque monitoring explained below. Other inputs may include the angular position of the ISG 14, or more specifically, the angular position of a rotor (θ_r) as measured by a first sensor, or position sensor 34.

[0019] In the embodiment shown in Figures 1 and 2, the ISG 14 is a three phase motor, having three motor currents, or phase currents: i_a, i_b, and i_c. The torque controller 30 only receives two of the three currents, because, as explained more fully below, there is a known relationship between any two of the currents and the third. Thus, as shown in Figure 2, the torque controller 30 receives currents i_{am} and i_{bm}.

[0020] In response to the inputs received, the torque controller 30 outputs voltage signals to the transformation function 32. Specifically, the transformation function 32 receives

signals related to voltages V_d, V_q, which represent the voltages along the d and q axes, respectively. The d-q axes are normal to each other, and represent a frame of reference that rotates with the rotor in the ISG 14. The transformation function 32 also receives the rotor position (θ_r), and transforms V_d and V_q into voltages along a fixed reference frame, V_x and V_y. A two phase to three phase converter 36 converts the two phase voltages V_x, V_y into three voltages V_a, V_b, and V_c, which are sent to the ISG 14.

[0021] The ISG 14 includes an inverter 38 and an interior permanent-magnet synchronous machine (IPMSM) 40. Of course, other electric machines could be used, for example, an induction machine. The inverter 38 receives DC power from the battery 22, and the voltage signals V_a, V_b, and V_c from the converter 36. The inverter 38 then outputs AC current i_a, i_b, and i_c to the IPMSM 40. The ISG 14 includes three current sensors 42, 44, 46 for measuring the currents i_a, i_b, i_c, respectively. Of course, current sensors need not be integrated into an inverter, such as the inverter 38, but rather, may be separate devices.

[0022] To verify the accuracy of the current sensors 42, 44, 46, the MCU 26 includes a current sensors monitor 48. The monitor 48 uses a sum current method to determine the

accuracy of the phase current measurements. In particular, the monitor 48 uses the following equation:

$$\left| i_a + i_b + i_c \right| \leq \varepsilon_I \qquad \text{Eq. 1}$$

[0023] where, i_a, i_b, i_c are the phase currents, and ϵ_I is a predetermined current value, chosen to be some very small value. In theory, the sum of the phase currents is zero; however, ϵ_I may be set to some small, non-zero value, and the accuracy of the current sensors 42, 44, 46 will still be verified.

[0024] The current sensors monitor 48 outputs a number of signals to an AC torque calculator 50. These signals include a signal D_i_sens, which indicates whether the current sensors 42, 44, 46 contain a fault, and current signals i_{am} and i_{bm}. Only two current signals are provided to the torque calculator 50, since the third current i_{cm} is known from Equation 1. Also provided as an input to the torque calculator 50 is θ_r, the position signal output from the position sensor 34.

[0025] A first, or AC torque, may be calculated using the following equation:

$$T_{AC} = \frac{3}{2} \cdot n_p \left[\psi_F i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq} \right] \quad \text{.............Eq. 2}$$

[0026] where n_p is the number of pole pairs in the IPMSM 40, L_s and I_s are stator inductance and current, respectively (with subscripts d and q indicating the frame of reference), and Ψ_F is the constant flux linkage produced by the permanent magnets in the IPMSM 40. Although Equation 2 accurately defines the AC torque in the ISG 14, in practice, it may be more convenient to determine the AC torque from a lookup table. Such a table correlates various currents with corresponding output torques for the ISG 14.

[0027] The position sensor 34 also outputs a signal to a speed estimator 52. The speed estimator 52 uses the change in angular position of the rotor in the ISG 14 over a known period of time to determine the rotor speed (ω_r). The speed estimator 52 then sends a signal related to ω_r to a speed sensor monitor 54.

[0028] The speed sensor monitor 54 also receives a signal (ω_{eng}) related to the speed of the engine 12. The engine speed and the speed of the ISG 14 are then compared, using the following equation:

$$\left|\omega_r - \omega_{eng}\right| \leq \varepsilon_\omega \qquad \text{Eq. 3}$$

[0029] where ϵ_ω is some small value. Thus, the speed sensor monitor 54 helps to ensure the integrity of the position sensor measurement and rotor speed calculation. When the engine 12 is disconnected from the ISG 14--e.g., when the disconnect clutch 20 is open--another speed, such as the speed of the PTU 16, can be used in place of the engine speed. Of course, a different value for ϵ_ω may need to be used.

[0030] The speed sensor monitor 54 then outputs signals to a DC torque calculator 56. The DC torque calculator 56 receives a signal related to the rotor speed, as well as a signal (D_ω_sens) indicating whether the speed sensor monitor 54 verified the speed of the rotor (ω_r). In addition, the DC torque calculator receives signals U_{DC} and i_{DC}, which are related to the voltage and current, respectively, output by the battery 22. Thus, the DC torque calculator 54 can calculate the power output from the battery 22 as the product of U_{DC} and i_{DC}.

[0031] Because not all of the power output from the battery 22 is received by the ISG 14, a more accurate DC torque calcu-

lation considers power losses from other electrical loads, such as the loads 24. In addition, the ISG 14 will inherently have some electrical power loss and some mechanical power loss. Therefore, the DC torque calculator 56 reduces the power output from the battery 22 by the power consumed by other electrical loads 24 and the power losses of the ISG 14, to determine a first motor power (P^*_{DC}). This relationship is illustrated in the following equation:

$$P^*_{DC} = P_{DC} - P_{LOADS} - P_{ELEC} - P_{MECH} \qquad \text{............Eq. 4}$$

[0032] where P_{DC} is the power output from the battery 22, P_{LOADS} is the power consumed by the loads 24, P_{ELEC} is the electrical power loss of the ISG 14, including losses in the inverter 38 and the IPMSM 40, and P_{MECH} is the mechanical power losses of the ISG 14. The torque calculator 56 then divides P^*_{DC} by ω_r to determine the DC torque of the ISG 14.

[0033] A torque comparison and arbitrator 58 then receives a signal (T_{AC}) from the AC torque calculator 50, and another signal (T_{DC}) from the DC torque calculator 56. In addition, the torque comparison and arbitrator 58 receives the sensor fault signals (D_ω_sens) and (D_i_sens), and the refer-

ence torque (T_{ref}). The torque comparison and arbitrator 58 then uses a number of equations to monitor the torque of the ISG 14.

[0034] First, it is determined whether the speed of the rotor (ω_r) is above a predetermined speed. If it is, the AC torque (T_{AC}) and the DC torque (T_{DC}) will be compared to each other. This is shown in the following equation:

$$\left|T_{AC} - T_{DC}\right| \leq \varepsilon_T \qquad \text{Eq. 5}$$

[0035] where ϵ_T is a first predetermined torque which may be chosen based on the confidence of the terms in Equation 4. For example, some of the power losses used in Equation 4 may be estimates having high or low confidence levels. Where the confidence levels are low, the value of ϵ_T may be chosen to be somewhat higher, because it will be expected that there will be a greater difference between the AC torque and the DC torque. Where the confidence levels in Equation 4 are high, however, ϵ_T may be relatively small, since the AC torque and the DC torque should be almost equal.

[0036] If the speed of the ISG 14--i.e., the rotor speed (ω_r)--is below the predetermined speed, the DC torque calculation

may not be accurate enough to use in Equation 5. As an alternative, the first motor power (P^*_{DC}) can be compared to a second, or AC motor power. The AC motor power (P_{AC}) is easily calculated as the product of the voltage and current of the ISG 14. Therefore, when ω_r is below the predetermined speed, the following equation can be used in place of Equation 5:

$$\left|P_{AC} - P^*_{DC}\right| \leq \varepsilon_p \qquad \text{Eq. 6}$$

[0037] where ϵ_p is a predetermined motor power which, like ϵ_T, depends on the confidence of the power loss terms used in Equation 4.

[0038] The torque comparison and arbitrator 58 also compares the reference torque (T_{ref}) to the AC torque as shown in the following equation:

$$\left|T_{AC} - T_{ref}\right| \leq \varepsilon_{ref} \qquad \text{Eq. 7}$$

[0039] where ϵ_{ref} is a reference torque that may be chosen based on a number of considerations. For example, ϵ_{ref} may be chosen based on an allowable deviation between an operator generated acceleration command and an actual vehi-

cle acceleration. Because the acceleration of the vehicle is directly related to the torque of the ISG 14, an allowable acceleration deviation is easily transformed into an allowable torque deviation(ϵ_{ref}).

[0040] After performing the calculations discussed above, the torque comparison and arbitrator 58 can then output one or more signals indicating the results of the torque monitoring. For example, if the relationships of the equations hold, the torque comparison and arbitrator 58 may put out a signal (T_m) related to the torque of the ISG 14, and indicating that the torque has been successfully monitored. Alternatively, if one or more of the relationships in the above-referenced equations do not hold, the torque comparison and arbitrator 58 may send a signal to shut down the ISG 14. In such a case, the signal could go through a fault filter 60 which would allow a time lapse Δt prior to the ISG 14 being completely shut down.

[0041] Of course, a torque comparison and arbitrator, such as the torque comparison and arbitrator 58, may output a wide variety of signals, which cause various actions to be taken on an electric motor and associated systems. For example, verifying the torque of an electric motor may be more or less critical, depending on whether the motor is

used to drive a vehicle, or is used in some other application. Therefore, as an alternative to shutting down the motor when there is a detected problem with the motor torque, the speed or torque of the motor could be reduced, or other systems adjusted to compensate for the detected torque fault.

[0042] In order to verify output from the MCU 26, the controller 28 can perform one or more verification calculations. As inputs, the controller 28 receives the reference torque (T_{ref}) and the phase currents (i_{abc}). The controller 28 can then compare a parameter value of the ISG 14 to a corresponding expected parameter value when the reference torque is zero. For example, the controller 28 can use a logic similar to that found in the field oriented torque controller 30 or the transformation function 32 to transform the phase currents i_{abc} into i_d and i_q in the rotating d-q reference frame--see, e.g., Equation 2. Because i_d and i_q should equal zero when the torque reference is zero, the controller 28 can apply the following equation:

$$i_d^{\ 2} + i_q^{\ 2} \leq \varepsilon_{I0} \qquad \text{Eq. 8}$$

[0043] where ϵ_{I0} is the current deviation tolerance when the ref-

erence torque is zero. Equation 8 is also valid for any two of the phase currents, i_a, i_b, i_c, which may be more convenient to use, since a transformation function is not required.

[0044] Similarly, V_d and V_q can be input from the field oriented torque controller 30. When the reference torque is zero, V_d should also be zero; however, V_q is dependent on the frequency (f_{ISG}) of the ISG 14 and the flux (Ψ_F) of the magnets in the ISG 14. Therefore, the controller 28 can also use the following equation:

$$\left| V_d^{\,2} + (V_q - f_{ISG}\Psi_F)^2 \right| \le \varepsilon_{V0} \quad \text{..........................Eq. 9}$$

[0045] where ϵ_{V0} is the voltage deviation tolerance when the reference torque is zero. Because Equation 9 contains the flux term (Ψ_F), which results from the presence of the permanent magnets in the IPMSM, the transformed voltages V_d, V_q are used. In the case of an induction machine, the flux term is not present, and any two of the voltages V_a, V_b, V_c can be used. If the controller 28 determines that the relationships in Equations 8 and 9 hold, nothing more needs to be done; however, if the relationships do not hold, the controller 28 can output a signal to shut down

the ISG 14.

[0046] Figure 3 shows a flow chart 62 which conveniently illustrates the method employed by the MCU 26. First, at step 64, the motor currents, or phase currents i_a, i_b, i_c are determined. Next, at step 66, the current sensors monitor 48 verifies the motor currents--see Equation 1. The AC torque is then determined by the AC torque calculator 50, by using a preprogrammed lookup table in which the motor current is compared to a list of motor currents in the table; a corresponding AC torque is then determined--see step 68.

[0047] The motor position, or the angular position (θ_r) of the rotor is measured by the position sensor 34 at step 70. At step 72, the speed estimator 52 then determines the motor speed based on the change in angular position of the rotor over some known period of time. The motor speed is then verified by the speed sensor monitor 54 using Equation 3--see step 74.

[0048] The DC torque calculator 56 then uses Equation 4 to determine the DC power--see step 76. At this point, it is determined whether the motor speed (ω_r) is above the predetermined speed--see decision block 78. If ω_r is above the predetermined speed, the DC torque calculator

56 then determines the DC torque by dividing the result of Equation 4 (P^*_{DC}) by the motor speed (ω_r)--see step 80. At step 82, the torque comparison and arbitrator 58 uses Equation 5 to determine the difference between the AC torque and the DC torque. If the motor speed (ω_r) is not above the predetermined speed, the AC power of the ISG 14 is determined based on the voltage and current of the ISG 14, both of which are easily measured--see step 84. At step 86, the torque comparison and arbitrator 58 compares the AC power to the DC power using Equation 6.

[0049] The torque comparison and arbitrator 58 then determines the torque reference (T_{ref}) from an input signal it receives--see step 88--and then compares the torque reference (T_{ref}) to the AC torque previously determined in step 68--see step 90. Finally, the controller 28 performs a check of the MCU 26 using Equations 8 and 9--see step 92. It is important to note that although many of the steps shown in the flow chart 62 are shown sequentially, they may in fact be performed in a different sequence, and some of the steps may be performed simultaneously.

[0050] Figures 4A, 4B, 5 and 6A-6C illustrate how the system 10 and method described above can be used to detect vari-

ous types of faults. For example, Figures 4A and 4B show voltage and current outputs, respectively, for a simulation representing a one phase inverter fault ($V_a = 0$) for a zero torque reference and a motor frequency of 100 rad/sec. Because the torque reference is zero, i_d and i_q should also be zero, and the relationship shown in Equation 8 should hold. An examination of Figure 4B, however, indicates that this is not the case. In fact, i_d and i_q each have an amplitude of approximately 20 amps. Thus, a controller, such as the controller 28, would detect the inverter fault based on an application of Equation 8.

[0051] Figure 5 shows simulation results of a current polarity fault for a reference torque of zero. As seen in the graph, the AC torque reaches a maximum level in approximately 0.1 seconds. This type of fault can be detected by a comparison of the AC torque with the reference torque, as shown in Equation 7.

[0052] Figures 6A-6C represent simulation results of an ISG having a position sensor fault. Figure 6A shows the currents i_d and i_q over some period of time. Figure 6B shows the voltage of an ISG over the same period of time, and Figure 6C shows the reference torque and the AC torque over an extended period of time. From Figure 6A, it is seen that the

currents i_d and i_q exhibit spikes. In Figure 6B, it is seen that the ISG voltage saturates at time instances 94. This saturation occurs when the position sensor readings are orthogonal to the rotor magnet flux orientation. Despite the position sensor fault, the average AC torque, shown in Figure 6C, follows the torque reference--even if it follows only weakly. This type of position sensor fault can be detected by verifying the zero reference conditions using Equations 8 and 9, or by comparing the AC torque with the torque reference, as in Equation 7.

[0053] While the best mode for carrying out the invention has been described in detail, those familiar with the art to which this invention relates will recognize various alternative designs and embodiments for practicing the invention as defined by the following claims.